Optisystem Simulation for Optical Communication in an Atmospheric Turbulence

by

Abdullah Omar bin Muhamad Fuad

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Electrical and Electronics Engineering)

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CERTIFICATION OF APPROVAL

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December 2009

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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ABDULLAH OMAR BIN MUHAMAD FUAD

ABSTRACT

Free-space optical (FSO) is one of the latest technologies nowadays used for transmitting and receiving signals. Although FSO has its advantages, it also has its side effects and one of them is the atmospheric turbulence which will be discussed in this project. In this particular project, the performance of optical communication in an atmospheric turbulence will be analyzed and simulated via Optisystem, one of optical simulation software. Before simulation is been done, it is necessary to understand the fundamental of FSO and how it works. FSO communication faces problems from optical signal scintillation that is introduced by atmospheric turbulence. Turbulence is caused by unstable temperature and pressure causing the change of index refraction in air. Due to this, the transmitted signals will have disturbance and the appropriate data will not be sent properly. This project will study the mechanism of atmospheric turbulence, identifing the techniques and formula proposed to represent the turbulence as well as to determine the best modulation scheme to analyze the performance of optical wave. In this research, information is gathered and analyzed. After going through the concepts, various solutions will be taken and tested in order to choose which will be the best method to overcome the problem. Expected result is that when atmospheric turbulence occurs in a strong degree, signal quality will be low. Whereas if weak turbulence occurs, the quality signal transmitted will be better. It is hoped that this project will enhance and improve the future communication in optical field for the betterment of humankind.

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LIST OF ABBREVIATIONS

FSO	Free Space Optics
BER	Bit Error Rate
NASA	National Aeronautics and Space Administration
WDM	Wavelength-division Multiplexing
APD	Avalanche Photodiode
OOK	On Off Keying
PSK	Phase Shift Keying
BPSK	Binary Phase Shift Keying
QPSK	Quadrature Phase Shift Keying
SNR	Signal to Noise Ratio
PAM	Pulse Amplitude Modulation

CHAPTER 1

INTRODUCTION

1. 1 Background of Study

Free space optical (FSO) communication is the latest technology as a solution to a high capacity of bandwidth demand due to the fast moving communication nowadays. FSO is a line-of-sight technology that transmits modulated beam of visible or infrared light through atmosphere. The need of a much higher-bandwidth, cost effective, good security and reduced time-to-market means of communication suites the FSO well. As we know, the most common and wide used technology currently in market is the fibre optic cable transmission medium.

An interesting fact about free space, or we see it as air is that, light travels faster through it (approximately 300,000 km/s) than it travels through glass (approximately 200,000 km/s). This is one of the best reasons why we are now exploring a new transmission medium that could give more advantage than what we have in the market. Another good advantage of FSO over fibre cable is that the installation of FSO will save a lot of cost in terms of hardware equipments. Other than that, FSO is a license-free product because it operates in the unregulated spectrum. In short, we could say that FSO offers an economic advantage over fibre medium transmission.

1.2 Problem Statement

1.2.1 Problem Identification

Although FSO has much more advantage than any other transmission medium that is currently used nowadays, FSO has its challenges to transmit signals through air. In an open medium like air, there are unpredictable disturbance such as fog, absorbtion, scattering, physical obstruction, building sway and atmospheric turbulence. In this project, we will mainly focus on the atmospheric turbulence that affects the channel of FSO transmission. By analyzing what happens through the channel during atmospheric turbulence occur will give us more understanding on the situation of the FSO and how to seek the best way to solve that particular situation.

1.2.2 Significant of project

Doing research for this project will provide us a firm answer of optical communication in an atmospheric turbulence situation. This project will show how atmospheric turbulence affect optical signal transferred and it will prove which method of modulation is better than the other methods during weak and strong atmospheric turbulence. By doing research on this, it will clarify what is needed for the free-space optical communication to improve the current technology and therefore it can be applied in the industry as a broadband communication replacing physical guided medium.

1.3 Objective of Project

Here are the objectives of this project

- To do a research on how FSO works and what are its limitation specifically in atmospheric turbulence.
- To research on modulation schemes used in FSO that will give the best modulated signal during atmospheric turbulence.
- To analytically run expressions and formulas based on background of atmospheric turbulence and what has been understood from research.
- To simulate and analyze using Optisystem software thus concluding the best method in solving the atmospheric turbulence problem.

1.4 Project Time Frame

The study & simulation on atmospheric turbulence in FSO is to be completed within approximately one year timeframe (two semesters). The scope for phase 1 of the project, which is research of the theoretical part, equations used, what are the considerations needed during simulation and other supportive information for the project will be completed by this semester. In phase 2, simulation will be done in order to see the result and report the findings from simulations. The result will be analyzed and assessed in order to obtain best result for the project.

CHAPTER 2

LITERATURE REVIEW

2.1 History of FSO

FSO has been developed by the military and NASA for more than 30 years back in various forms. Although it has been used since then, we commonly know about fiber-optic communication nowadays due to it's widely acceptance in the telecommunication industry. Compared to fiber-optic communication, FSO is still relatively new. FSO gives alternative to the guided medium communication that is currently using fiber where FSO enables to transmit similar bandwidth capacity, using similar transmitter and receiver and even enable WDM technology to operate through free space.

2.2 How FSO works

2.2.1 An Overview

Free-space optics operates in the infrared spectral range. The available wavelength for optic transmission is close to the visible spectrum which is around 850 to 1550nm which means it operates around 200THz frequency range. One good advantage about FSO is that it does not require operating license due to the usage of FSO is not regulated under the Malaysian Communications and Multimedia Comission nor other communication comission around the world. [1]

The main requirement of FSO system is unobstructed line-of-sight environment. Physical objects such as tree or walls will disable the travelling of light from transmitter to receiver.

In the transmitter side of FSO, there will be the light source and a telescope. This telescope is designed using either lenses or a parabolic mirror which will narrow the beam and projects it towards the receiver. The transmitted beam picked up at the receiver will be focused to a photo detector using lens or mirror. In practical, the received signal is much smaller than the size of trasmitted beam. Therefore, part of the signal transmitted is lost during transmission process.

FSO can operate in full duplex operation. It means that the transmitted and received information can be transfered at the same time. Therefore this increases the feasbility of using FSO due to its capability of doing multitasking job in one time. [1]

2.2.2 Transmitter

At the transmitter side of an FSO system, there are a few things to be considered. They are the laser used to transmit the signal and the modulation used. The laser which stands for Light Amplification by Stimulated Emission of Radiation used here is a semiconductor laser. These type of lasers are relatively small in size, high power and cost efficient. In Table 1 shows compund used in semicondutor laser and what are their correspond wavelength. The modulation scheme will be explained in part 2.4.

Table 1: Compund of semi conductor laser and its wavelength [1]

Compund	**Wavelength, um**
GaInP	0.64-0.68
GaAs	0.904
AlGaAs	0.8-0.9
InGaAs	1.0-1.3
InGaAsP	0.9-1.7

2.2.3 Receiver

After been transmitted through the channel the laser are then received and been demodulated to retrieve back the original signal. A few things also need to be considered at the receiver, among them is the photo diode used to detect lasers. For a short wavelength application (approx. 850nm), silicon detectors are the best choice. In silicon detector, there are two most common type used which is PIN detector and Avalanche Photodiode. For transmition in a long distance, APD is the best choice than PIN. However, using APD will be more expensive due to its requirement to have a stable and high-bias voltage. [1]

2.3 Modulation of optical communication signals

In optical communication system the block diagram is as shown below

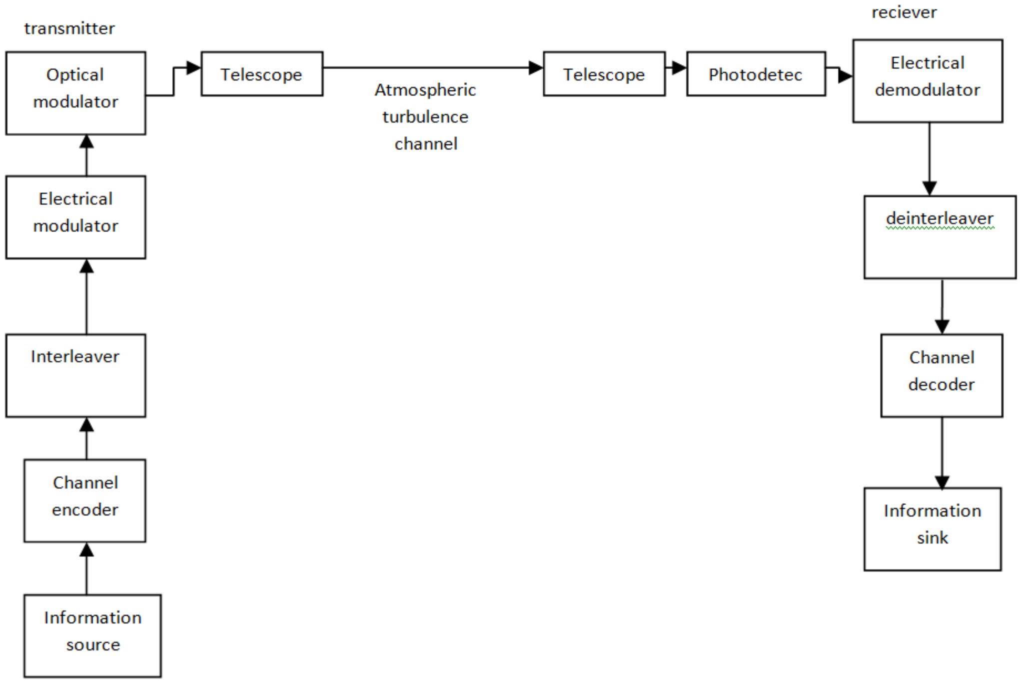


Figure 1: Optical communication block diagram [3]

In Figure 1, information source will be encoded and interleaved and then modulated into an electric waveform by an electrical modulator. In the optical modulator, the intensity of light source is modulated by the output signal of electrical modulator. The light source is transmitted using telescope to the atmosphere. Turbulence occurs at the channel part as shown above.

In the electrical modulation block, the signal to be transmitted will be modulated in various methods of modulation techniques. The most used in the optical communication system field are:

i. On-off Keying (OOK)

ii. Phase Shift Keying (PSK) which consist of two widely used modulation techniques; Binary Phase Shift Keying (BPSK) & Quadrature Phase Shift Keying (QPSK)

These modulation techniques will improve the signal transmission as it is one of the factors that we can control unlike whether and environment situation. Therefore when we control the modulation technique of the light beam, we will get lesser bit error rate (BER) and higher signal to noise ratio (SNR)

2.4 On-off Keying (OOK)

On-off keying (OOK) is a type of modulation that represents digital data as the presence or absence of a carrier wave. OOK is one of the amplitude shift keying modulation scheme where we can see in Figure 2 that the amplitude of the signal varies according to the bit transmitted. In other words, we can explain that the presence of a carrier for a specific duration represents a binary one, while its absence for the same duration represents a binary zero. [4-6]

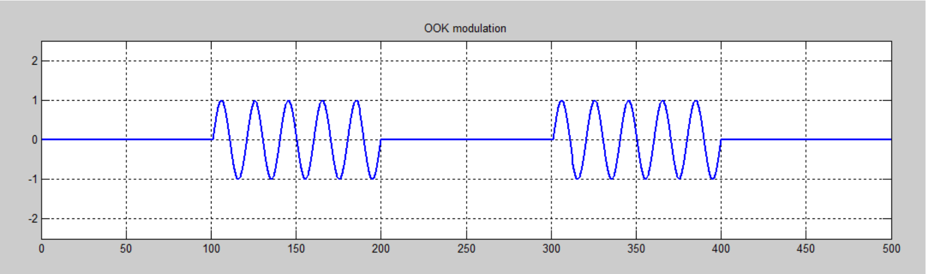


Figure 2: OOK waveform (0 1 0 1 0)

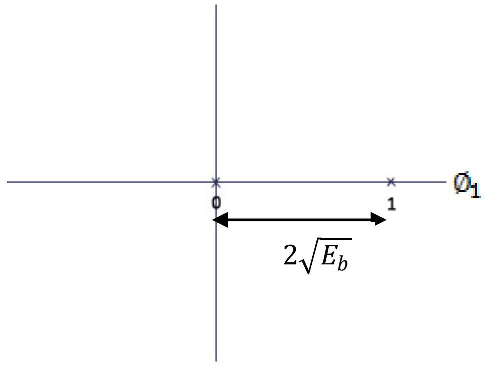


Figure 3: Constellation Diagram of OOK

The constellation diagram of OOK is shown in Figure 3 where the distance between its bit is given by $2\sqrt{E_b}$

2.5 Binary Phase Shift Keying (BPSK) & Quadrature Phase Shift Keying (QPSK)

Phase-shift keying (PSK) is a digital modulation scheme that conveys data by changing, or modulating, the phase of a reference signal (the carrier wave).

BPSK is the simplest form of PSK which it uses two phases which are separated by 180° and so can also be termed 2-PSK. It does not particularly matter exactly where the constellation points are positioned, and in Figure 4 they are shown on the real axis, at 0° and 180°. [4-6]

These two phases are separated by $180°$. They are represented as below:

$$s_1(t) = \sqrt{\frac{2E_b}{T_b}}\cos\left(2\pi f_c t\right) \textit{ [represents symbol ‘1’]} \tag{2.1}$$

$$s_2(t) = \sqrt{\frac{2E_b}{T_b}}\cos\left(2\pi f_c t + \pi\right) = -\sqrt{\frac{2E_b}{T_b}}\cos\left(2\pi f_c t\right) \quad \textit{[represents symbol ‘0’]} \tag{2.2}$$

Where T_b is the bit duration and E_b is the transmitted signal energy per bit. $\frac{E_b}{T_b}$ is the signal power. From the equation above, we can see that there is only one basis function of unit energy that is,

$$\emptyset_1(t) = \sqrt{\frac{2}{T_b}}\cos(2\pi f_c t), \qquad 0 \le t < T_b \tag{2.3}$$

Therefore we can express $s_1(t)$ and $s_2(t)$ in term of $\emptyset_{\mathbf{1}}(t)$ as follows:

$$s_1(t) = \sqrt{E_b}\emptyset_1(t), \quad 0 \le t < T_b \tag{2.4}$$

$$s_2(t) = -\sqrt{E_b}\emptyset_1(t), \quad 0 \le t < T_b \tag{2.5}$$

BPSK system is characterized by having a signal space that is one-dimensional (in-phase), with a signal constellation consisting of two message points. The coordinate of the points are

$$s_{11} = \int_0^{T_b} s_1(t)\emptyset_1(t)\,dt$$

$$= +\sqrt{E_b}$$

$$s_{21} = \int_0^{T_b} s_2(t)\emptyset_1(t)\,dt$$

$$= -\sqrt{E_b}$$

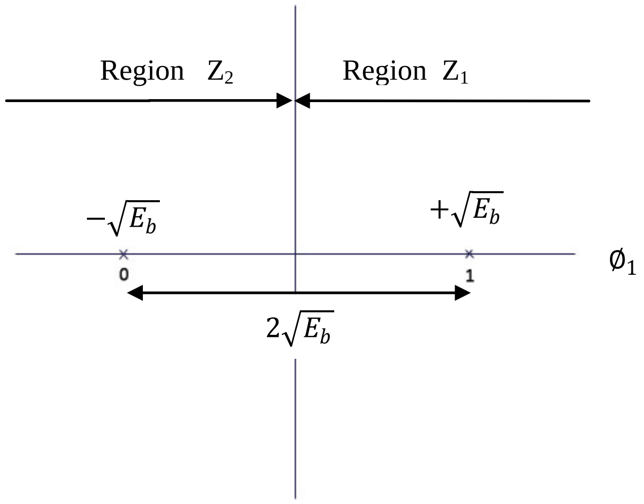


Figure 4: Constellation diagram of BPSK

In Figure 4, we see that the points representing ‘1’ and ‘0’symbols have their own region, Z_1 and Z_2. These regions will mark their threshold level to receive the appropriate signal transmitted. For example, when a transmitter transmits bit 1, it must retrieve in Region Z^1 in order for it to be processed into bit 1. Exceeding the threshold level, which means entering Region Z_2 will give an error to the signal.

The distance from one bit to another is $2\sqrt{E_b}$. The bigger the distance of the bit, the lower the bit error rate (BER) [6].

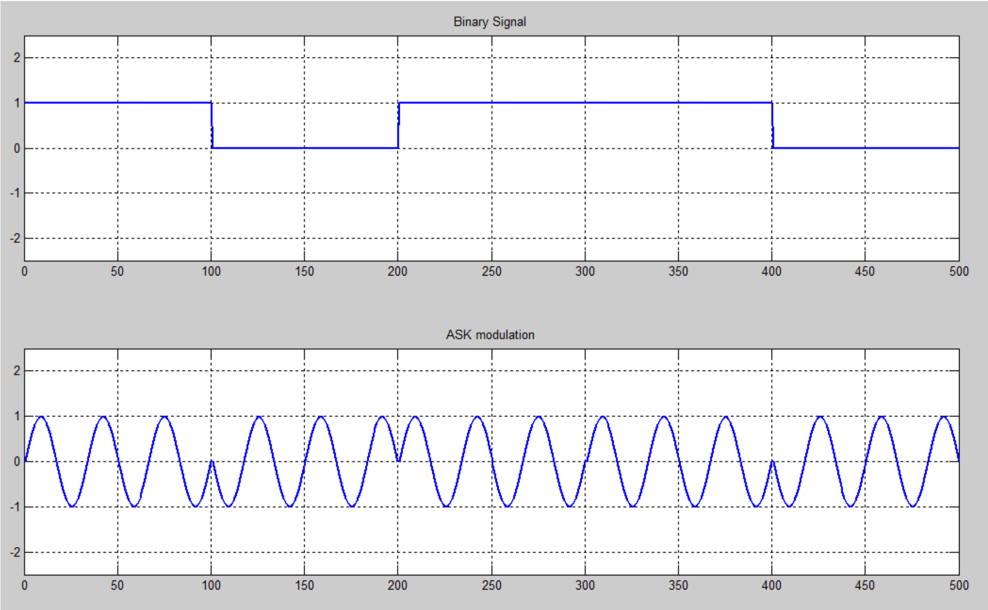


Figure 5: Waveform of BPSK (1 0 1 1 0)

In the signal shown in Figure 5, every change of logical bit, there will be a change in phase at the output frequency waveform.

QPSK uses four points on the constellation diagram, equispaced around a circle such as π/4, 3π/4, 5π/4 and 7π/4. With four possible phases, QPSK can encode two bits per symbol, shown in the diagram with Gray coding to minimize the BER — twice the rate of BPSK. We may define the transmitted signal of QPSK as below

$$s_i(t) = \begin{cases} \sqrt{\frac{2E}{T}} \cos\left[2\pi f_c t + (2i-1)\frac{\pi}{4}\right], & 0 \leq t \leq T \\ 0, & \text{elsewhere} \end{cases} \quad (2.6)$$

Where i = 1, 2, 3, 4; E is the transmitted signal energy per symbol, and T is the symbol duration. f_c is the carrier frequency equals n_c/T for fixed integer $n_{c.}$ Each value of phase represents a unique dibit (00,01,11,10), where only a single bit is changed from one dibit to another.

Using one of the trigonometric identity which is,

$$cos\ (\alpha+\beta) = cos\ \alpha\ cos\ \beta - \sin\alpha \sin\beta$$

We may use Equation 2.6 to redefine $s_i(t)$ in the equivalent form:

$$s_i(t) = \sqrt{\frac{2E}{T}} \cos\left[(2i-1)\frac{\pi}{4}\right] \cos 2\pi f_c t - \sqrt{\frac{2E}{T}} \sin\left[(2i-1)\frac{\pi}{4}\right] \sin 2\pi f_c t \qquad (2.7)$$

where i =1, 2, 3, 4.

Base on the above equation, we then can make the following observation:

i. There are two orthonormal basis functions, $\emptyset_1(t)$ and $\emptyset_2(t)$. Both functions are defined by a pair of *quadrature carrier*.

$$\emptyset_1(t) = \sqrt{\frac{2}{T}} cos(2\pi f_c t), \qquad 0 \le t < T \qquad (2.8)$$

$$\emptyset_2(t) = \sqrt{\frac{2}{T}} sin(2\pi f_c t), \qquad 0 \le t < T \qquad (2.9)$$

ii. There are four message points, and the associated signal vectors are define by

$$\boldsymbol{s_i} = \begin{bmatrix} \sqrt{E}\ cos\left((2i-1)\frac{\pi}{4}\right) \\ -\sqrt{E}\ sin\left((2i-1)\frac{\pi}{4}\right) \end{bmatrix}, \quad i = 1,2,3,4$$

Table 2: QPSK phases and its input dibit

Phase of QPSK Signals (rad)	Input dibit
π/4	11
3π/4	10
5π/4	00
7π/4	01

Constellation diagram of QPSK is shown in Figure 6 where the dibit symbols are represented starting from ‘11’ at 45° (π/4). It is then separated by 90° for the next symbol, ’01’ at 135° (3π/4). The full representation of QPSK symbols are shown in the Table 2. The order of the dibit is sorted so that there will only be one bit change at a time for the next symbol representation. [4-6]

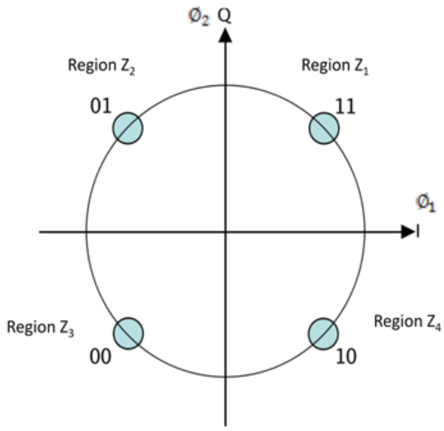


Figure 6: Constellation diagram of QPSK

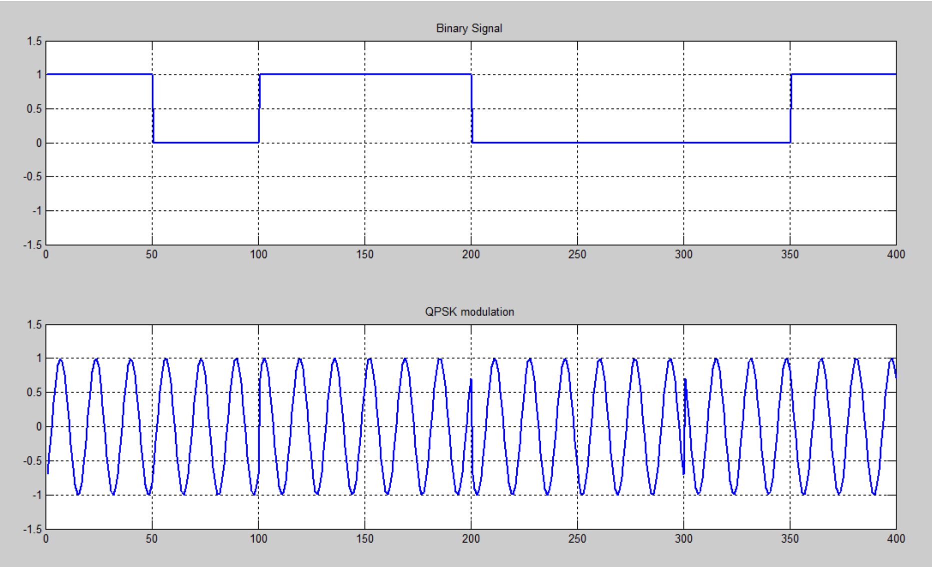


Figure 7: Waveform of QPSK (1 0 1 1 0 0 0 1)

Advantage of QPSK than BPSK is either:

i. double the data rate of BPSK while maintaining the bandwidth of the signal

OR

ii. maintain the data-rate of BPSK but half the bandwidth needed

2.6 Atmosphere Condition

In FSO, the atmosphere acts as the channel in transferring and receiving the signals. Therefore, understanding the channel is one of the most important elements in analyzing and applying FSO. The atmosphere can cause degradation and attenuation to FSO system which in the end will contribute to channel fade, disturbance of transmitted information or even signal lost. This happens due to local condition and uncontrolled weather. For example, the weather can contribute large amounts of water vapour or heat in the air that will cause scattering and varied degree of beam laser for transmission.

2.6.1 Atmospheric Turbulence

Hot and dry climates may cause turbulence to the transmission system. When the ground heats up, the air also heats up and makes the air cell heated up. In the air cell, some of the air cells or air pockets are heated up more than the others which then causes change in index of refraction due to different index in one space. This will then cause the change of path that the light takes while it propagates through air. Moreover, the change of index refraction happens in a random motion. [1] This is called atmospheric turbulence. Below is a diagram showing what turbulence is all about.

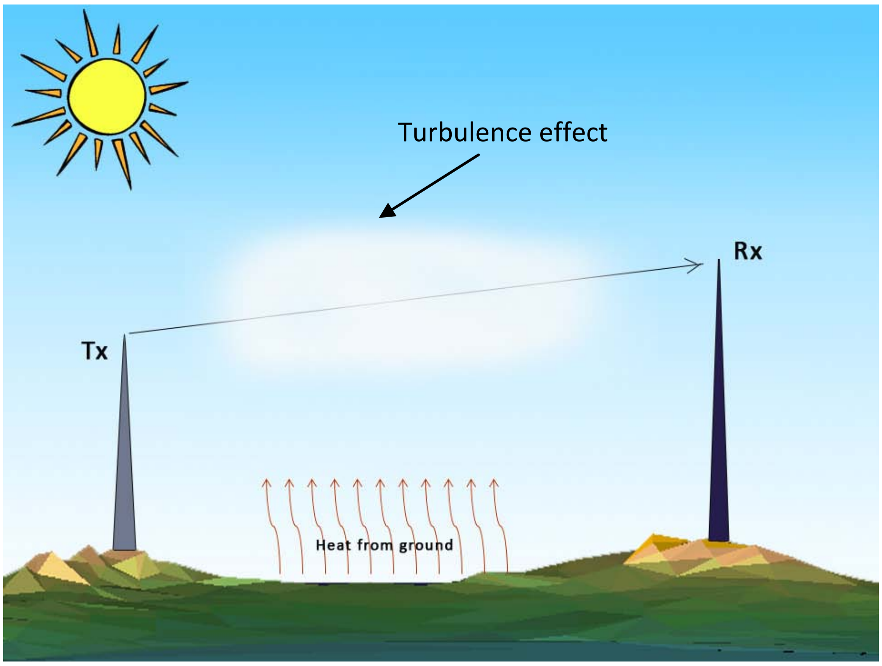


Figure 8: Atmospheric Turbulence effect due to heat from ground

Atmospheric turbulence effect can be expressed as mathematical equation as below

$$P(t) = A(t)\, Ps(t) + n(t)$$

Where P(t) is the received optical signal at the receiver, A(t) is the atmospheric turbulence represented in log normal distribution, $P_s(t)$ is the optical signal that is been transmitted in the transmitter and n(t) is the additive white Gaussian noise.

From the equation above, we can draw a block diagram representing the equation as in Figure 9;

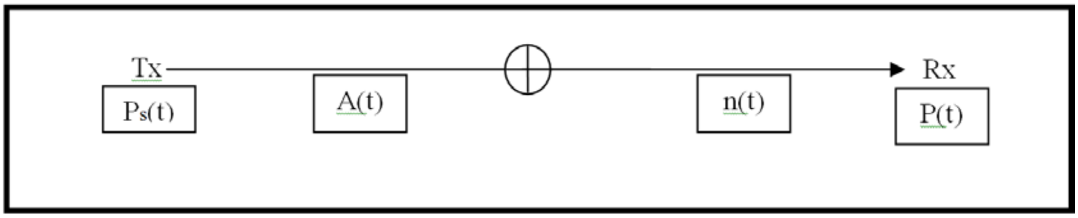


Figure 9: Concept of communication in atmospheric turbulence channel

Laser beams experience three effects under turbulence which are beam wander, scintillation and beam spread. Beam wander means that the beam is deflected randomly through the changing refractive index cells. Scintillation is caused by varied phase front of the beam, producing intensity fluctuations. Lastly, beam spread is due to beam spreading more than diffraction theory prediction. [1]

2.6.2 Scintillation

Out of the three turbulence effect mentioned above, scintillation is the most affected phenomena towards FSO. Scintillation is the change of light intensity in time and space along the signal path. The change of light intensity is caused by the different index refraction which acts like a series of small lenses that deflects the portion of light beam into and out of the transmission path. This can cause the light beam to scatter and shoots in multipath.

Scintillation effect follows a log-normal distribution, characterized by variance σ_i, for a plane wave given by:

$$\sigma_i^2 = 1.23 C_n^2 k^{7/6} L^{11/6} \tag{2.10}$$

where σ_x is the scintillation attenuation, C_n is the level of turbulent intensity, k is equal to $2\pi/\lambda$ where λ is frequency of the laser transmitted and L is the length of link in metres. [1]

2.6.3 Impact of other weather

There are several other weather conditions that would give impact to the FSO system in practical. They are:

2.6.3.1 Fog

Fog is one of the weather that causes most damage in FSO because it composes small water droplets with radii about the size of near infrared wavelength. Fog occurs when visibility ranges from 0 – 2000 meters. Fog is normally described in the term “thin fog” or “dense fog”. If the visibility is more than 2,000 meters, the condition is referred to hazy. On the other hand, if visibility is less than 2,000 meters, we categorize the condition as foggy. Scattering is the dominant loss of mechanism for fog.

Fog is not well understood and it is difficult to be characterized physically. Density distribution of fog particles can also vary with height. This makes the modelling of fog harder and more complex.

2.6.3.2 Snow

Snowflakes come in variety shape and size of ice crystals. Snowy weather can attenuate the beam but it scattering effect has no significant because the size of snowflakes is larger when compared to operating wavelength of FSO. Link attenuation potential is approximately 3 dB/km to 30 dB/km.

2.6.3.3 Rain

Rain has lesser impact than foggy weather. This is because the radius of raindrops (200-2000 μm) is significantly larger than the wavelength of typical FSO light source.

Rain attenuation is moderate in nature. For example if a 2.0 cm/hour rainfall drops, signal attenuation of 5.5 dB/km can be observed. The available commercial FSO system that operates in 25 dB link margin can easily penetrate rain. However, then the rain rate increases beyond 10cm/hour, rain attenuation will have to be taken into consideration. Nevertheless, this whether condition does not impact much because it lasts only a short period of time. [1]

CHAPTER 3

METHODOLOGY

3.1 Procedure Identification

There are some procedures to be followed in order to carry out and implement the project. This is to ensure that the project can be accomplished within the given timeframe.

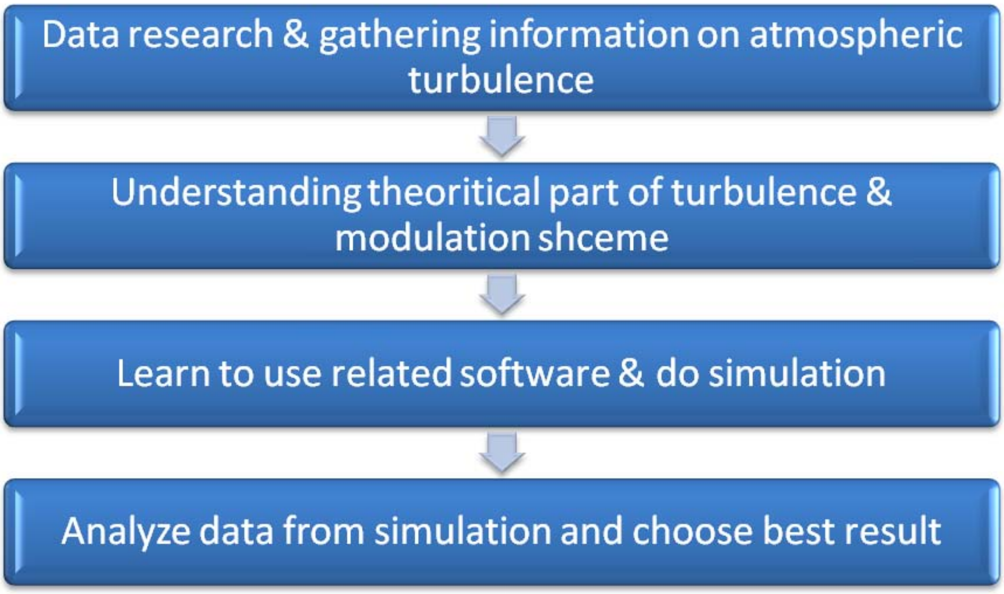


Figure 10: Flow chart of project

3.1.1 Data research and gathering

Elements of projects involved in this stage include the study of atmospheric turbulence, optic communication condition in the atmosphere such as to what modulation scheme must be used, what are the theories needed to be consider and how can the optic communication be improved in transmitting through air.

3.1.2 Analyze mathematical equations from theory

After finishing the research, appropriate mathematical equations will be analyzed for certain criteria needed to simulate the atmospheric turbulence in FSO. We will see what equation fits the channel during turbulence and non-turbulence condition.

3.1.3 Simulate using Optisystem

Next step is to build an optical block diagram using Optisystem as simulation tool to simulate the FSO channel in atmospheric turbulence condition and see what will happen to the signal transmitted. Parameters in the simulation are set according to what has been researched.

3.1.4 Analyzing and choosing best solution

In this stage, the output simulation will be analyzed and compared to the theoretical part either it matches or not or it will give certain new results. The best solution from simulation will be summarized and presented as the solution of the project.

3.2 Tools

The Optisystem v7.0 created by Optiwave Systems Inc will used throughout this project in order to simulate what happens during transmission of optical signal in FSO with strong and weak turbulence. OptiSystem is a comprehensive software design suite that enables its users to plan, test, and simulate optical links in the transmission layer of modern optical networks.

Most calculation, graph plotting and plugging in equation are done in Microsoft Office Excel.

CHAPTER 4

RESULTS & DISCUSSION

4.1. Modulation Techniques Considered

We then analyze the probablity of bit error rate equations for each modulation scheme considering turbulence and without tubulence

4.1.1 On Off Keying (OOK)

In this case, the probability of bit error rate (BER) for OOK modulation scheme is given by

$$P_e = P_0 P(r > T / OFF) + (1 - P_0)(r < T / ON) \tag{4.2}$$

where P_0 and P_1 are the transmission probability of bits "0" and "1," respectively. Further, $P(r > T / OFF)$and $P(r < T / ON)$ are BERs corresponding to bits 0 and 1, respectively. The BER also can be written as below

$$P_e = P(0)P(1/0) + P(1)P(0/1) \tag{4.3}$$

When the signal transmitted corresponding to bit 0 is zero, the received signal corresponding to this bit will have only AWGN and the level for a_i is equal to -1. Therefore, the probability error when bit 0 is sent is shown below

$$P(0/1) = P(n > T) = Q\left(\frac{1}{\sigma}\right) \quad \text{where the threshold, } T = 1.$$

while the probability error of signal when bit 1 is sent

$$\mathrm{P(1/0)} = Q\left(\frac{1}{\sigma}\right)$$

The total of BER when bit "0" and "1" is sent can be shown below

$$P_{e(0,1)} = P(0)P(1/0) + P(1)P(0/1)$$

$$= P(0)Q\left(\frac{1}{\sigma}\right) + P(1)Q\left(\frac{1}{\sigma}\right)$$

$$= Q\left(\frac{1}{\sigma}\right)(P(0) + P(1))$$

$$= Q\left(\frac{1}{\sigma}\right)$$

The BER for this OOK scheme when there is no turbulence and only AWGN is present, will be

$$P_e = Q\left(\sqrt{\frac{E_b}{\sigma_g^2}}\right) \tag{4.4}$$

where E_b energy per bit is is equal to $a_i = 1^2 = 1$, Q is the complementary error function while σ_g^2 is the Gaussian noise.

Next we consider when there is turbulence occur or the signal is affected by fading where the amplitude information is damaged. We assume that at the receiver has the knowledge of the fading which introduced by turbulence. AWGN noise is representing as σ_g^2

In this case, the probability error when bit 1 is sent is

$$P(0/1) = P(2A(t) + n(t) < T) \tag{4.5}$$

So, the probability error of signal when bit 0 is sent

$$P(n > T) = P\left(N[0,1] > \frac{T}{\sigma_g}\right) = Q\left(\frac{T}{\sigma_g}\right)$$

$$P(0/1) = \frac{e^{-\frac{\sigma^2}{2}}}{\sigma_g\sqrt{2\pi}}\int_0^\infty \frac{1}{x^2}e^{-\frac{\ln^2 x}{2\sigma^2}}\left[\int_{-\infty}^{T}\frac{e^{-\frac{(r-2x)^2}{2\sigma_g{}^2}}}{\sigma_g\cdot\sqrt{2\pi}}dr\right] \tag{4.6}$$

The total BER of OOK with turbulence fading can be written as

$$P_e = P_0 Q\left(\frac{T}{\sigma_g}\right) + \frac{e^{-\frac{\sigma^2}{2}}\left(1 - P_0\right)}{\sigma\sqrt{2\pi}} \int_0^\infty \frac{1}{x^2} \cdot e^{-\frac{\ln^2 x}{2\sigma^2}} \cdot Q\left(\frac{2x - T}{\sigma_g}\right) dx \qquad (4.7)$$

During simulation, equation (4.4) and (4.7) will be taken and analyzed in MATLAB.

4.1.2 Phase Shift Keying (PSK)

4.1.2.1 Binary Phase Shift Keying (BPSK)

For BPSK modulation, the signals are only in phase. There is no signal at the quadrature region where $s_q = n_q = 0$. First consideration, when there is no turbulence at the medium channel $(A(t)) = 1$ and AWGN is zero $\sigma_g = 0$. When the bit 0 is sent, $s = -1$ and the probability of error can be written as

$$P(1,0) = Q\left(\frac{\alpha}{\sigma_g}\right)$$

While when the bit 1 is sent, the level signal $s = 1$ and the BER signal can be written as

$$P(0/1) = P\left(\frac{\alpha + n}{2} < 0\right) = P(n < -\alpha) = P(n > \alpha)$$

$$= P\left(N[0,1] > \frac{\alpha}{\sigma_g}\right)$$

$$= Q\left(\frac{\alpha}{\sigma_g}\right)$$

So the total error in this case when the bit 0 and 1 is sent can be written as

$$P_e = P(0)P(1/0) + P(1)P(0/1)$$

$$= P(0)Q\left(\frac{\alpha}{\sigma_g}\right) + P(1)Q\left(\frac{\alpha}{\sigma_g}\right)$$

$$= Q\left(\frac{\alpha}{\sigma_g}\right) + \underbrace{[P(0) + P(1)]}_{1}$$

$$= Q\left(\frac{\alpha}{\sigma_g}\right)$$

The BER for BPSK modulation without turbulence is

$$P_e = \sqrt{\frac{E_b}{\sigma_g^2}} \tag{4.8}$$

where $E_b = \alpha^2 s^2(t) = \alpha^2$. This situation is same with $\alpha = 1$ and no fading. The above equation is simplified from from the equation below

$$\frac{\alpha}{\sigma_g} = \sqrt{\frac{\alpha^2}{\sigma_g{}^2}} = \sqrt{\frac{Eb}{\sigma_g{}^2}}$$

Next we will consier BPSK with turbulence. When the bit 0 is sent, the level of s is equal to -1 and the probability of error can be written as

$$P(1/0) = P(-\alpha A + n > 0)$$

$$= P(\alpha A - n < 0)$$

$$= P(\alpha A + n < 0)$$

When the bit 1 is sent, the level of s is equal to +1 which is

$$P(0/1) = P(\alpha A - n < 0)$$

Therefore, the total of BER in BPSK modulation when turbulence is considered

$$P_e = \int_0^\infty \frac{e^{-\sigma 2/2}}{y^{2\cdot}\sigma.\sqrt{2\pi}}.^{-\ln^2 y/2\sigma^2} Q(\infty) = Q(\infty)\int_0^\infty PDF_A dx = Q(\infty)\cdot 1 = 0 \tag{4.9}$$

4.1.2.2 Quadrature Phase Shift Keying (QPSK)

The total probability error in QPSK signal can be written as

$$P_e = P(00)P(err/00) + P(01)P(err/01) + P(10)P(err/10) + P(11)P(err/11) \quad (4.10)$$

When bit 00 is sent, the probability of error can be written as

$$P(err/00) = P\left(\frac{\left(\alpha/\sqrt{2} + n_i\right)}{2} < 0 \qquad or \ \frac{\left(\alpha/\sqrt{2} + n_q\right)}{2} < 0\right)$$

We can conclude that the probability of di-bit in QPSK is the same because it is symmetry. The total probability of error in QPSK without turbulence can be written as

$$P(err/00) = P(err/01) = P(err/10) = P(err/11) = 2Q - Q^2 \quad (4.11)$$

and

$$P_{err} = \left(2Q\left(\frac{\alpha}{\sigma_g.\sqrt{2}}\right) - Q^2\left(\frac{\alpha}{\sigma_g.\sqrt{2}}\right)\right)[P(00) + P(01) + P(10) + P(11)]$$

$$= 2Q\left(\frac{\alpha}{\sigma_g.\sqrt{2}}\right) - Q^2\left(\frac{\alpha}{\sigma_g.\sqrt{2}}\right) \quad ; \ \alpha_2 = Eb$$

$$= 2Q\left(\sqrt{\frac{\alpha^2}{2\sigma_g^2}}\right) = 2Q\left(\sqrt{\frac{Eb}{\sigma_g^2}}\right) \ ; \ \text{with } Eb = \frac{\alpha^2}{2} \quad (4.12)$$

We then consider QPSK with turbulence by taking again the probability error of QPSK in equation (4.10) and (4.11). When the same calculation is done, we find that

$$P_e = 2\int_0^\infty A(y)Q\left[\frac{y\alpha/\sqrt{2}}{\sigma_g}\right]dy$$

$$P_{e(total)} = 2.\frac{e^{-\sigma^2/2}}{\sigma\sqrt{2\pi}}\int_0^\infty \frac{1}{x^2}e^{-\ln^2 y/2\sigma^2}\,Q\left(\frac{x\alpha}{\sigma_g.\sqrt{2}}\right)dx \quad (4.13)$$

Attempts to equate and analyze the equations above using MATLAB was done but there has been some problem in obtaining graph when integrating Q function in MATLAB.

4.2 Calculation of Scintillation Variance

Before proceeding with the simulation in Optisystem, there are a few parameters that we must obtain from the scintillation variance equation that has been mentioned previously in Chapter 2 which is;

$$\sigma_i^2 = 1.23 C_n^2 k^{7/6} L^{11/6}$$

where σ_x is the scintillation variance, C_n is the level of turbulent intensity, k is equal to $2\pi/\lambda$ where λ is frequency of the laser transmitted and L is the length of link in metres. From the equation above, here are the parameters taken and assumed:

Table 3: Parameters in scintillation variance calculation

C_n	Level of turbulent intensity: 1.00E-12 (considered strong turbulence) to 1.00E-16 (considered weak turbulence)
λ	considered as 850nm (usually implemented in industry)
L	taken from 500m to 7000m

After inserting the parameters, a graph is plotted to see the relation between C_n (turbulence intensity) and length if link (L). The graph plotted is as in Figure 11.

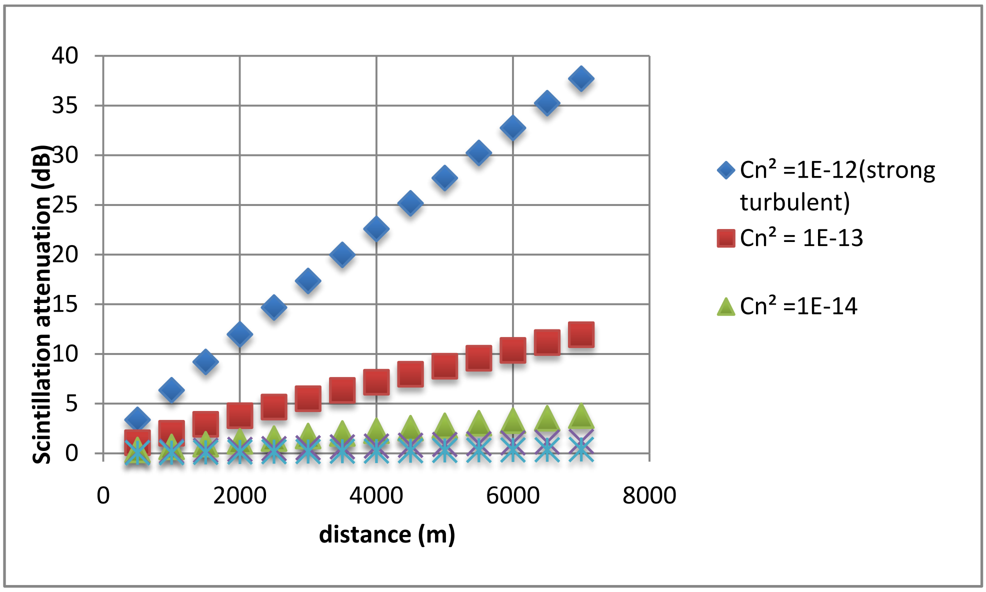


Figure 11: Graph of scintillation attenuation (dB) V.S distance (m)

From the graph above, we can see that in strong turbulence condition, the scintillation attenuation increases rapidly. On the other hand, a weak turbulence condition shows that the scintillation attenuation does not change rapidly and stays in a low dB value. This proves the theory of turbulence effect towards the scintillation attenuation where the higher the turbulence, the more scintillation attenuates. The detailed calculation of scintillation variance equation is shown in a table in **Appendix 1**.

4.3 Simulation using Optisystem

4.3.1 Using same distance but different turbulence

From total calculation in **Appendix 1**, we take the distance 2500m to be simulated in Optisystem. For this specific distance, we took the value of scintillation attenuation from the strongest turbulence to the weakest. These values will then be inserted in the FSO channel in simulation.

Table 4: Calculated σx for different turbulence intensity at distance 2500m

Type of turbulence	1.00E-12 (strong turbulence)	1.00E-13	1.00E-14	1.00E-15	1.00E-16 (weak turbulence)
Value of σ_x	14.66881	4.638685922	1.466881	0.463869	0.146688

The optical blocks in Optisystem is then built as shown below

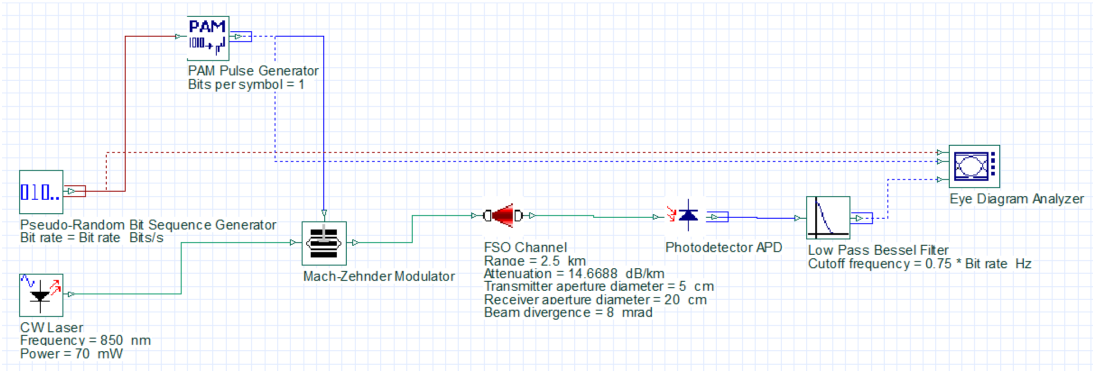


Figure 12: Block layout in Optisystem

In the block layout shown above, we start by placing a Pseudo-Random Bit Sequence Generator. This generator is connected to a pulse generator that acts as a modulator. We chose PAM Pulse Generator as the modulation scheme used in this simulation which a 2-PAM is equivalent to the OOK modulation. Next we take the Mach-Zehnder Modulator and connect the output of PAM Pulse Generator with a Continuous Wave (CW) laser block. Mach-Zehnder modulator modulates the intensity of laser light in response to an electric signal coming from the PAM Pulse Generator.

We then take the output of Mach-Zehnder modulator and insert a FSO Channel block where the optical signal will go through. The output of FSO channel will be connected to the APD Photodetector block and will go through low pass Bessel filter. We take Bessel filter as it has a flat group delay response. After the signal is been filtered, we take an Eye Diagram Analyzer to analyze. An eye diagram analyzer is chosen here to see the signal effect as it can be used to see the performance of the received signal.

Below are the parameters used in the block layout shown in Figure 12.

Table 5: Parameters used in Optisystem blocks

Type of block	Parameters type & value
Pseudo-Random Bit Sequence Generator	- No change has been made -
CW Laser	• Frequency = 850nm • Power = 70mW
PAM Pulse Generator	• Bit per symbol = 1
Mach-Zehnder Modulator	- No change has been made -
FSO Channel	• Range = 2.5km • Attenuation = follow according to Table 4 (in sweep mode) • Transmitter Aperture Diameter = 5cm • Receiver Aperture Diameter = 20cm • Beam divergence = 8mrad
Photodetector APD	- No change has been made -
Low pass Bessel filter	• Cutoff frequency = 0.75xBit rate

Simulation button is pressed and eye diagram is analyzed. In the eye diagram analysis, there are a few type of analysis that can be considered. But for this particular chapter we will only focus on the height of the eye diagram which will indicate the signal distortion and minimum BER which indicates the incorrect decision of retrieving the received signal into its original signal.

The higher the height of eye diagram, the better the received signal is due to minimum signal distortion. While the minimum value of BER, the better the signal is to be retrieved back. Below are the simulated results;

<table>
<tr>
<td>Min BER: 0

Eye Height: 1.50158e-5

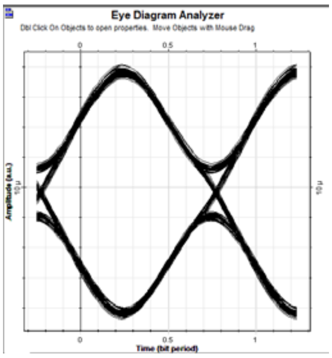


Figure 13: Eye Diagram at Cn = 1.00e-16 (WEAK TURBULENCE)</td>
<td>Min BER: 0

Eye Height: 1.2355e-5

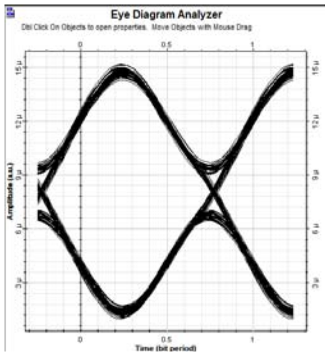


Figure 14: Eye Diagram at Cn = 1.00e-15</td>
</tr>
<tr>
<td>Min BER: 2.95952e-119

Eye Height: 6.52499e-6

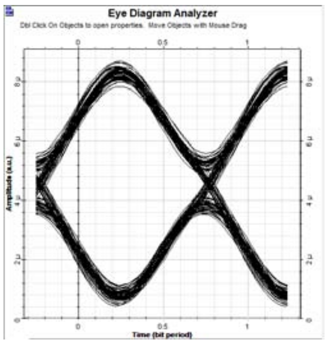


Figure 15: Eye Diagram at Cn = 1.00e-14</td>
<td>Min BER: 6.17847e-5

Eye Height: 2.618e-7

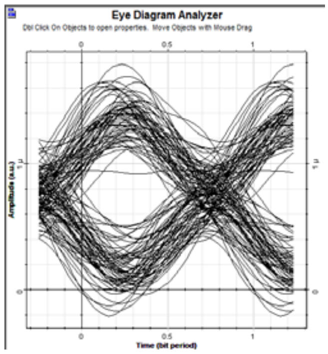


Figure 16: Eye Diagram at Cn = 1.00e-13</td>
</tr>
<tr>
<td colspan="2">Min BER: 1

Eye Height: 0</td>
</tr>
</table>

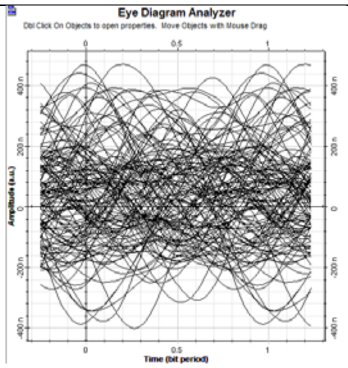


Figure 17: Eye Diagram at Cn = 1.00e-12 (STRONG TURBULENCE)

We can see briefly from the eye diagram analyzer image that when simulation is done from the weak turbulence intensity to a strong intensity, the eye height of eye diagram will decrease. This shows that when strong turbulence occur, the signal distortion increases until it becomes untraceable due to turbulence with given distance. We could also observe that minimum BER increases as turbulence increase which indicates that when strong turbulence occur, signal is badly affected until it could not be retrieved back at the receiver to get its original signal.

The summary of changing distance for different turbulence is shown in table below

Table 6: Different distance condition for different turbulence

	500	1000	1500	2000	2500	3000	3500	4000	4500	5000
Cn = 1E-12	✓	✓	✓	✘	✘	✘	✘	✘	✘	✘
Cn = 1E-13	✓	✓	✓	✓	✓	✘	✘	✘	✘	✘
Cn = 1E-14	✓	✓	✓	✓	✓	✓	✘	✘	✘	✘
Cn = 1E-15	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Cn = 1E-16	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

4.3.2 Changing distance and parameters

A few other simulations with the same modulation (OOK) scheme have been done which are by varying the distance together with the turbulence intensity. Also we tried to modify a few parameters in the Optisystem block layout to see what happens to the signal.

In the simulation where we varied the distance together with turbulence intensity, it can be concluded that in a strong turbulence, the signal can only travel to approximately a maximum distance of 1500m. While in weak turbulence, travelling more than 5000m can still be acceptable. But if the signal travels over 7000m, the signal starts to distort badly. The eye diagram for this simulation can be seen in **Appendix 2**.

In terms of parameters, we tried to simulate in using distance of 1500m (the furthest it can go in strong turbulence condition using distance step size of 500m) while changing a few settings. Below are the effects of parameter change that we tried to simulate;

Table 7: Effect of parameter change in Optisystem block

Parameter Type	Changes done	Effect (change of eye height)
Transmitter Aperture Diameter	From 5cm to 10 cm	Decrease
Receiver Aperture Diameter	From 20cm to 40cm	Increase
Beam divergence	From 8mrad to 6mrad	Increase
Power of CW Laser	70mW to 100mW	Increase

The eye diagram figures are shown in **Appendix 3**.

The objective of this project is to see the different modulation scheme effect to the optical signal. But we could not manage to proceed with the simulation as this Optisystem version could not support the higher modulation scheme such as BPSK & QPSK. Therefore, we could not manage to change the modulation block in this simulation. This matter will be discussed further in the next chapter.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

As a conclusion, free space optics has its limitation in atmosphere although it is one of the fastest medium to transfer data from one place to another. The higher the atmospheric turbulence, the lower the data signal can be transmitted. Simulation for various modulations could not be done due to software limitations. Initially it is expected that simulation can be done to analyze different modulation scheme in order to obtain the best modulation scheme after simulating through different turbulence and parameters. But realizing that the Optisystem software was not the latest software gave limitation to this project. Therefore, analyzing only for 2-PAM modulation (OOK) only can prove us the theoretical of atmospheric turbulence but not the best modulation that can be used to transmit the data. Although in theory says that the best modulation is QPSK, it cannot be proven by simulation due to software limitation.

5.2 Recommendation

We have tried the very best in fulfilling the project objective and here are the results of it. Further recommendations to be made are to try and see what the real range of atmospheric turbulence is and compare it to the real situation that is affecting the atmosphere turbulence especially in Malaysia where we have sunlight most of the day time. Doing a real experimental work on scintillation effect in Malaysia would be a good exploration to the FSO technology in contributing to the country as not many people have been developing this technology locally.

REFERENCES

[1] Willebrand and S.Ghuman. (2001). *Free-Space Optics: Enabling Optical Connectivity in Today's Networks*, Indianapolis, Indiana, USA: Sams Publishing.

[2] Jagtar Singh and V.K. Jain (2008) .*Performance Analysis of BPPM and M-ary PPM Optical Communication Systems in Atmospheric Turbulence,* Technical Review, I.I.T Delhi, New Delhi, India.

[3] Qi Lu and Qingchong Liu. (2004). *Performance Analysis for Optical Wireless Communication System Using Subcarrier PSK Intensity Modulation through Turbulent Atmospheric Channel*, IEEE Communication Society.

[4] Simon Haykin (2001). *Communication System 4th Edition*, New York, USA: John Wiley & Sons, Inc.

[5] S.K. Venkata Ram. (2003). *Digital Communications*, New Delhi, India: S.CHAND,

[6] V.K.Jain, (2009). *Digital Transmitter Structur,* Lecture Note, Universiti Teknologi PETRONAS, Perak, Malaysia.

[7] Lucie Dordov´a and Otakar Wilfert, 2009, *Laser Beam Attenuation Determined by the Method of Available Optical Power in Turbulent Atmosphere*, Journal, Brno University of Technology, Czech Republik.

APPENDICES

APPENDIX 1:

Table of calculated scintillation variance equation

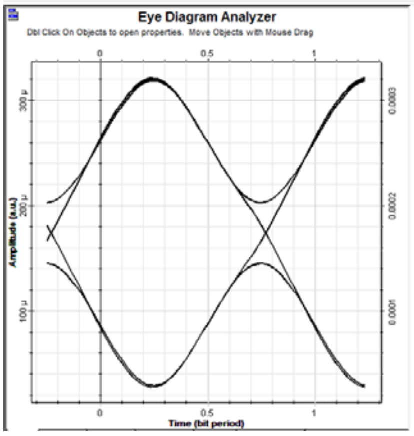
Table of Scintillation Attenuation for various turbulence intensity and different length

		Cn_1 1.0E-12		Cn_2 1.0E-13		Cn_3 1.0E-14		Cn_4 1.0E-15		Cn_5 1.0E-16
various L (length)	σ_x^2 (dB^2)	σ_x (dB)	σ_x^2 (dB^2)	σ_x (dB)	σ_x^2 (dB^2)	σ_x (dB)	σ_x^2 (dB^2)	σ_x (dB)	σ_x^2 (dB^2)	σ_x (dB)
500	11.255589	3.354935	1.1255589	1.06092361	0.11255589	0.335494	0.011255589	0.106092	0.001125559	0.033549
1000	40.109433	6.333201	4.01094326	2.00273395	0.40109433	0.63332	0.040109433	0.200273	0.004010943	0.063332
1500	84.347968	9.184115	8.43479678	2.90427216	0.84347968	0.918411	0.084347968	0.290427	0.008434797	0.091841
2000	142.93047	11.95535	14.2930466	3.78061458	1.42930466	1.195535	0.142930466	0.378061	0.014293047	0.119554
2500	215.17407	14.66881	21.5174071	4.63868592	2.15174071	1.466881	0.215174071	0.463869	0.021517407	0.146688
3000	300.57504	17.3371	30.0575041	5.48247244	3.00575041	1.73371	0.300575041	0.548247	0.030057504	0.173371
3500	398.73693	19.9684	39.8736933	6.314562	3.98736933	1.99684	0.398736933	0.631456	0.039873693	0.199684
4000	509.33451	22.56844	50.9334507	7.13676753	5.09334507	2.256844	0.509334507	0.713677	0.050933451	0.225684
4500	632.09306	25.14146	63.2093057	7.95042802	6.32093057	2.514146	0.632093057	0.795043	0.063209306	0.251415
5000	766.7755	27.69071	76.6775499	8.75657181	7.66775499	2.769071	0.766775499	0.875657	0.07667755	0.276907
5500	913.17379	30.21877	91.3173788	9.55601271	9.13173788	3.021877	0.913173788	0.955601	0.091317379	0.302188
6000	1071.1029	32.72771	107.110293	10.3494103	10.7110293	3.272771	1.071102926	1.034941	0.107110293	0.327277
6500	1240.3966	35.21926	124.039662	11.1373095	12.4039662	3.521926	1.240396623	1.113731	0.124039662	0.352193
7000	1420.9041	37.69488	142.090406	11.920168	14.2090406	3.769488	1.42090406	1.192017	0.142090406	0.376949

APPENDIX 2:

Simulation result of different distance with different turbulence intensity

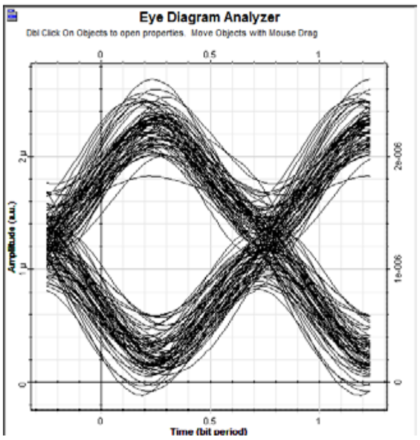
Simulation for Strong Turbulence (Cn = 1.00E-12) for different distance



Distance: 500m

Min BER = 0

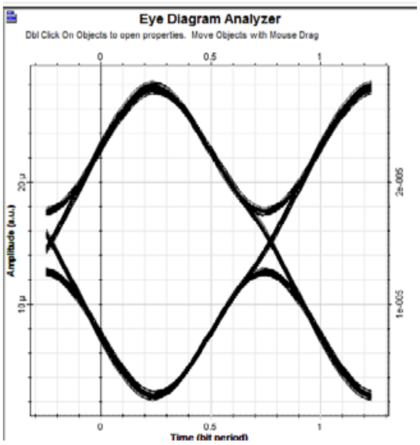
Max Eye Height: 0.000286527



Distance: 1000m

Min BER = 0

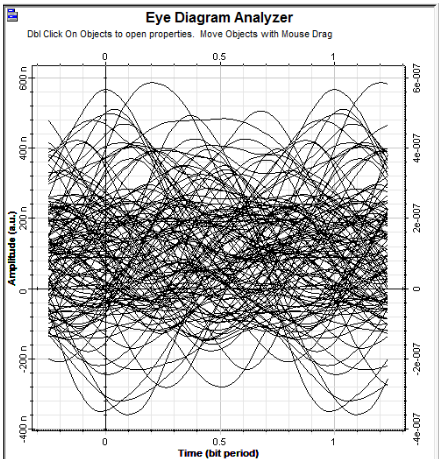
Max Eye Height: 2.4102e-005



Distance: 1500m

Min BER = 6.66423e-011

Max Eye Height: 1.07305e-006

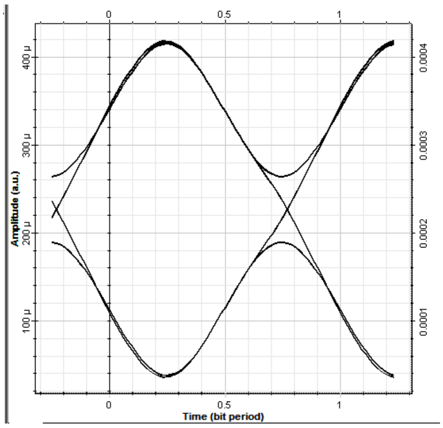


Distance: 2000-5000m

Min BER = 1

Max Eye Height: 0

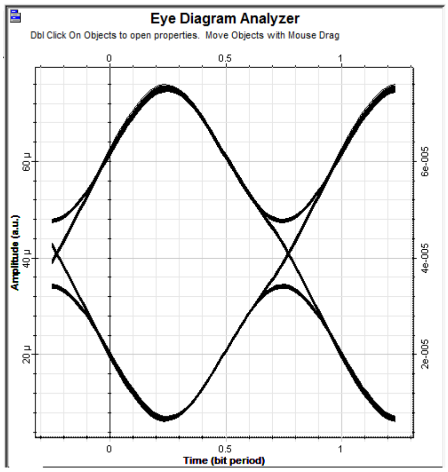
Simulation for Strong Turbulence (Cn = 1.00E-13) for different distance



Distance: 500m

Min BER = 0

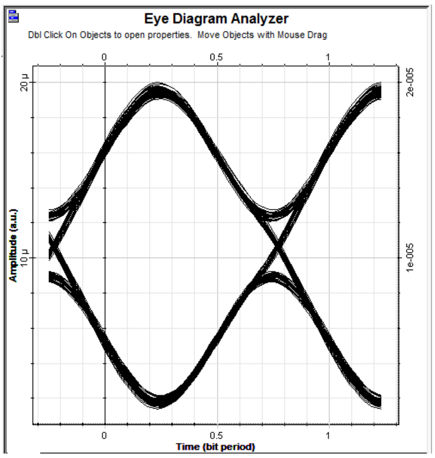
Max Eye Height: 0.000373



Distance: 1000m

Min BER = 0

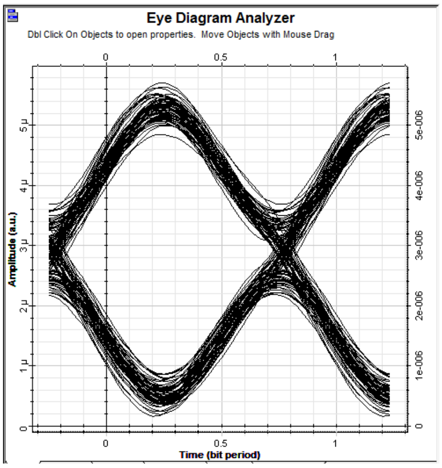
Max Eye Height: 6.679e-5



Distance: 1500m

Min BER =0

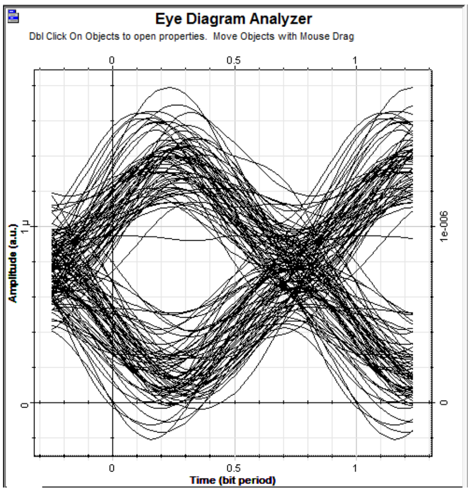
Max Eye Height: 1.66863e-5



Distance: 2000m

Min BER =6.263E-51

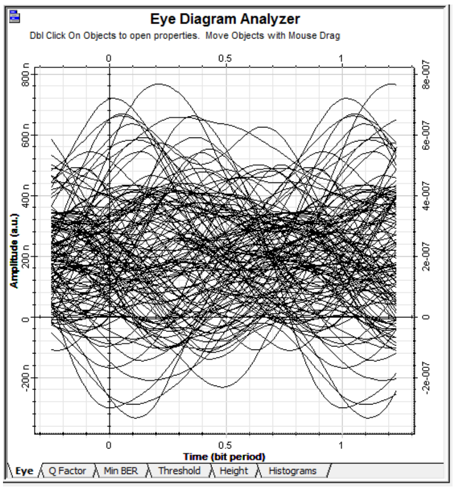
Max Eye Height: 3.8117E-6



Distance: 2500m

Min BER =6.178E-5

Max Eye Height: 2.618E-7

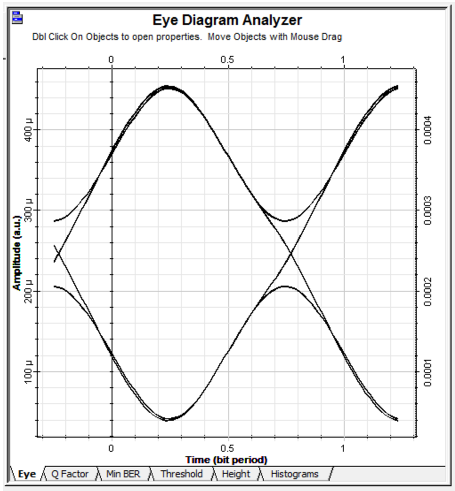


Distance: 3000-5000m

Min BER =1

Max Eye Height: 0

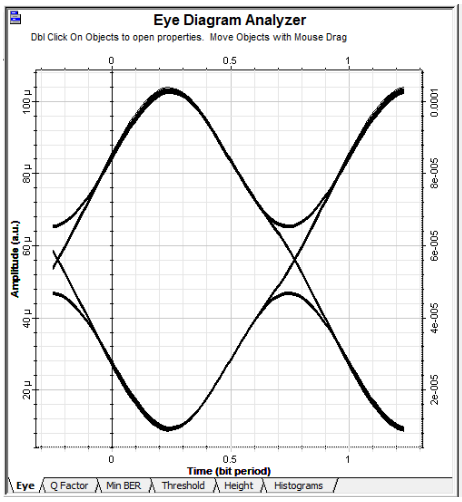
Simulation for Strong Turbulence (Cn = 1.00E-14) for different distance



Distance: 500m

Min BER =0

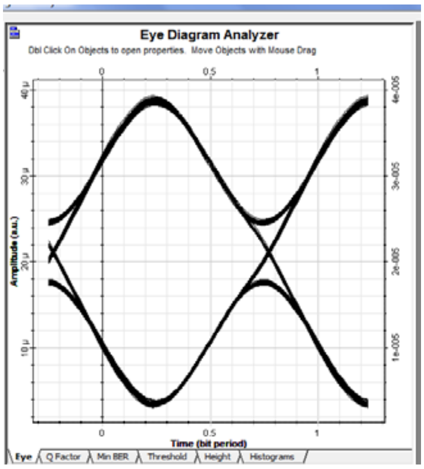
Max Eye Height: 0.0004058



Distance: 1000m

Min BER =0

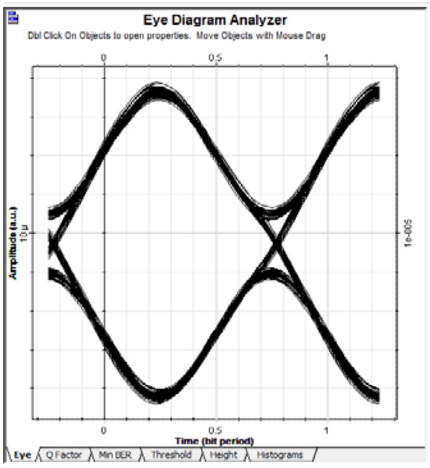
Max Eye Height: 9.183E-5



Distance: 1500m

Min BER =0

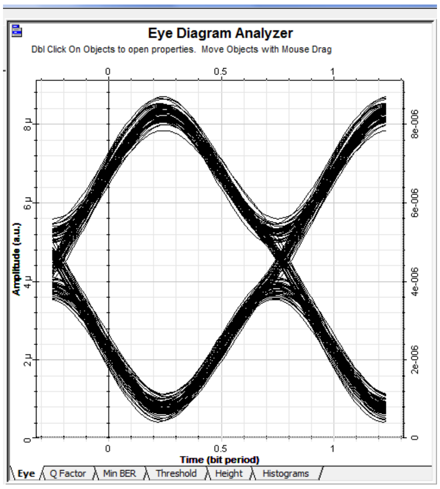
Max Eye Height: 3.40218E-5



Distance: 2000m

Min BER =0

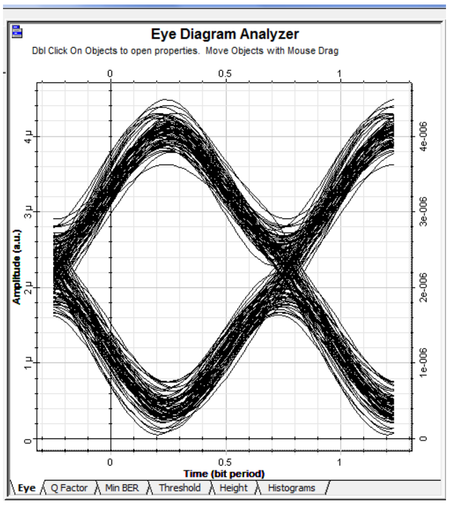
Max Eye Height: 1.46833E-5



Distance: 2500m

Min BER =2.95952E-199

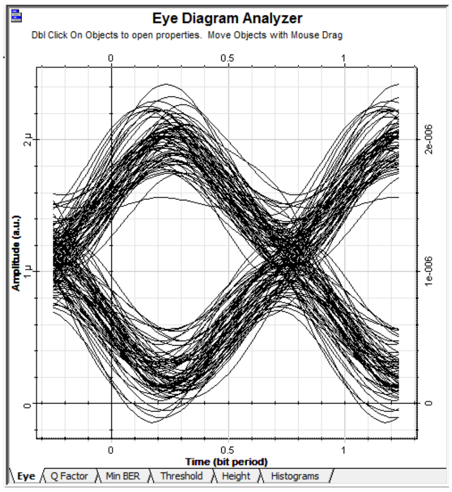
Max Eye Height: 6.524E-6



Distance: 3000m

Min BER =4.3465E-31

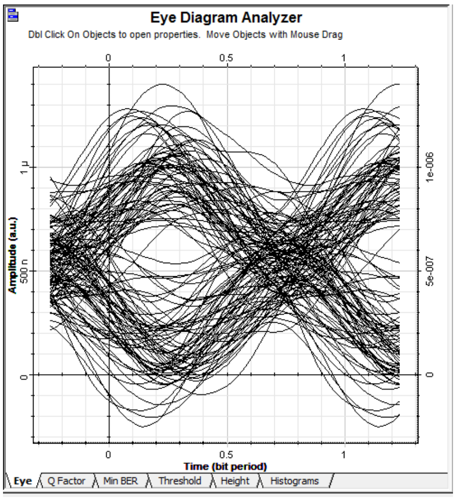
Max Eye Height: 2.7033E-6



Distance: 3500m

Min BER = 7.5E-9

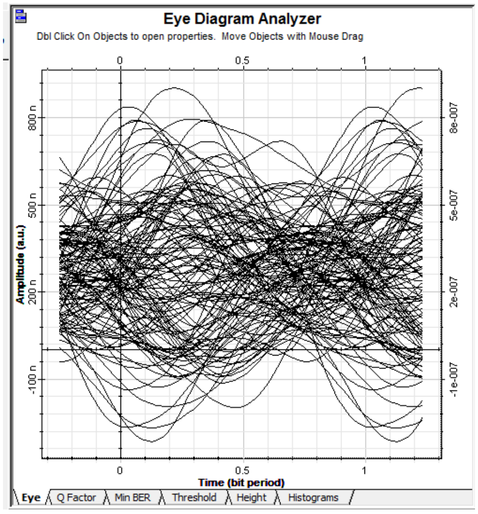
Max Eye Height: 8.33166E-7



Distance: 4000m

Min BER = 0.003343

Max Eye Height: -8.96814E-8

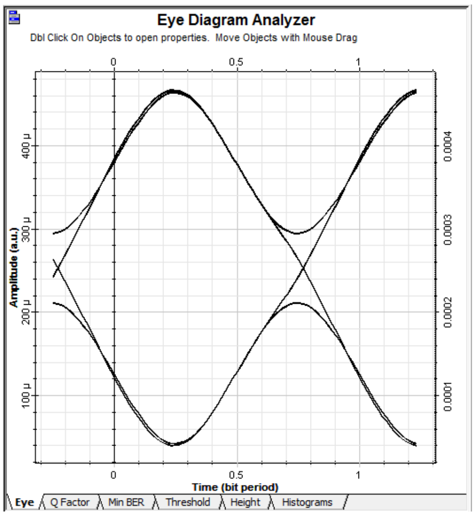


Distance: 4500-5000m

Min BER = 1

Max Eye Height: 0

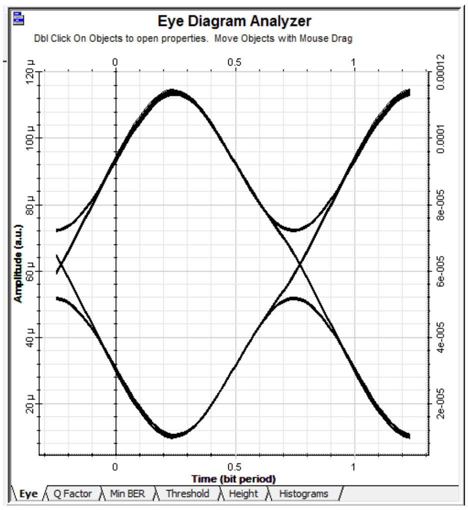
Simulation for Weak Turbulence (Cn = 1.00E-15) for different distance



Distance: 500m

Min BER = 0

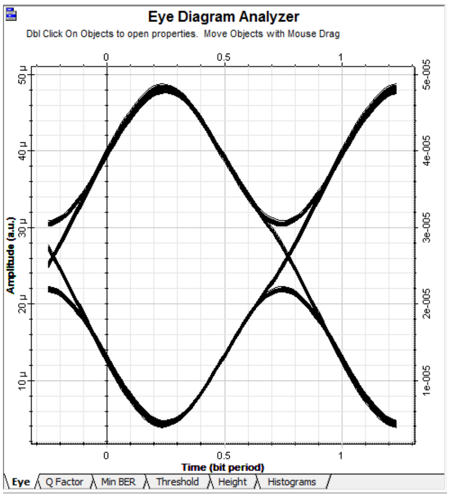
Max Eye Height: 0.0004167



Distance: 1000m

Min BER = 0

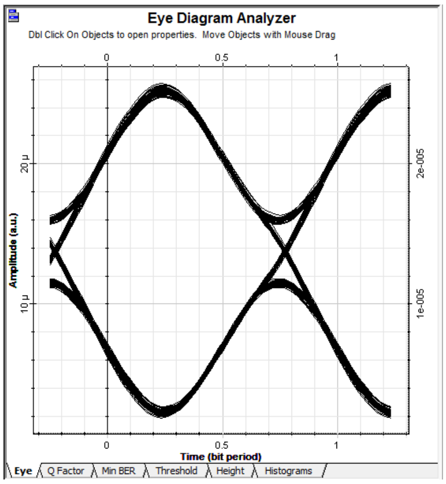
Max Eye Height: 0.00010153



Distance: 1500m

Min BER = 0

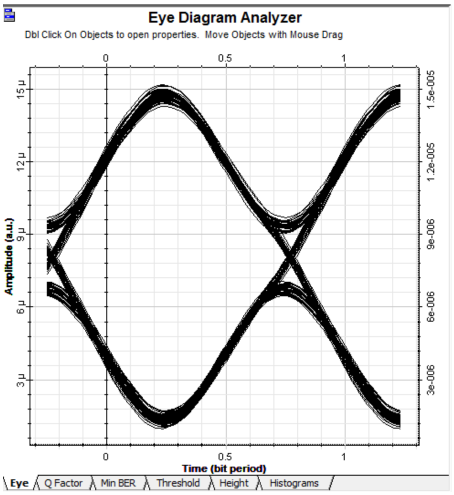
Max Eye Height: 4.247E-5



Distance: 2000m

Min BER = 0

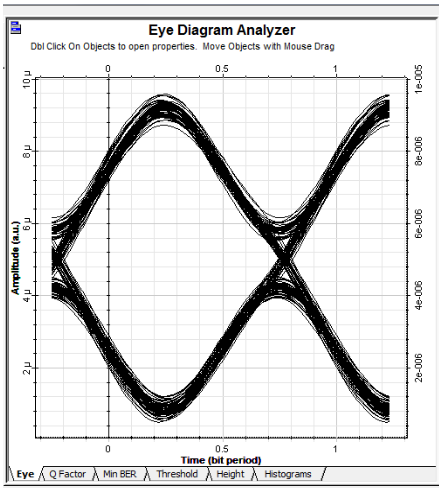
Max Eye Height: 2.1815E-5



Distance: 2500m

Min BER = 0

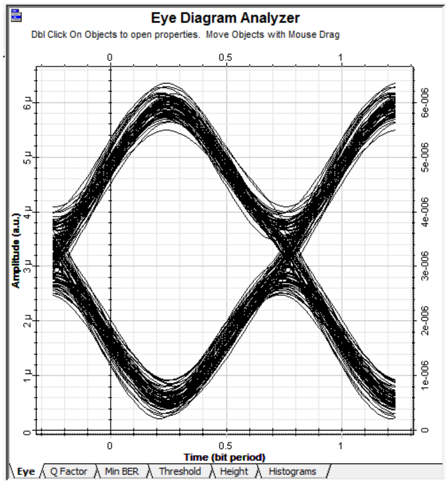
Max Eye Height: 1.2355E-5



Distance: 3000m

Min BER = 1.6699E-144

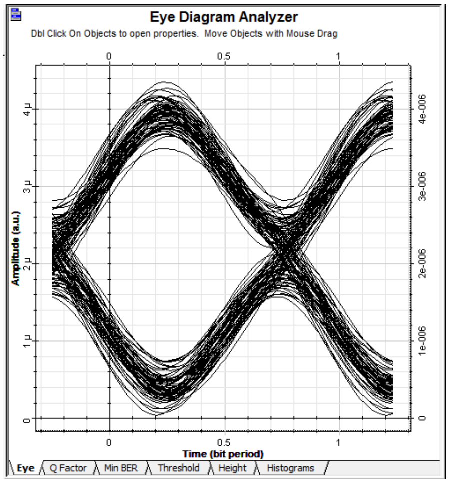
Max Eye Height: 7.3255E-6



Distance: 3500m

Min BER = 2.81318E-63

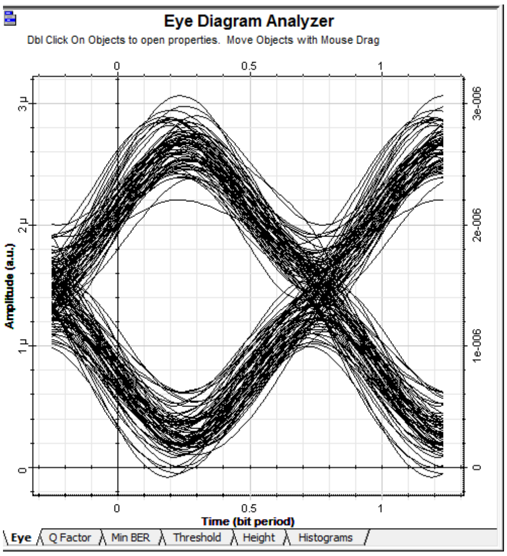
Max Eye Height: 4.3943E-6



Distance: 4000m

Min BER = 3.347E-29

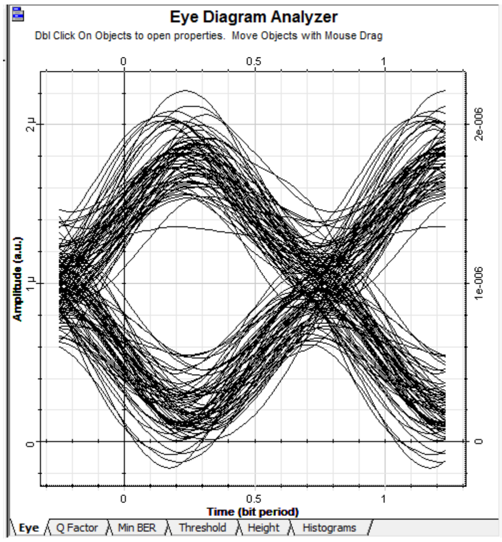
Max Eye Height: 2.58E-6



Distance: 4500m

Min BER = 3.1317E-14

Max Eye Height: 1.415E-66

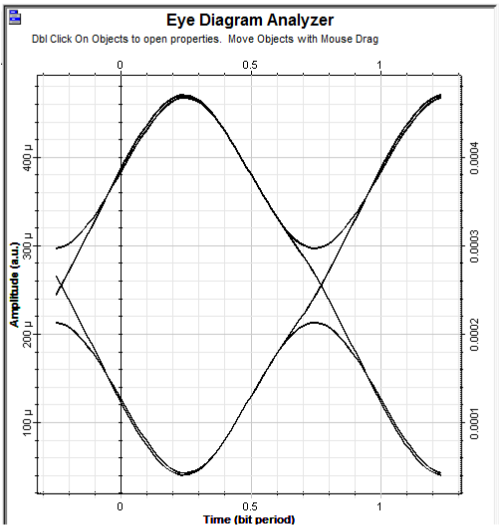


Distance: 5000m

Min BER = 2.005E-7

Max Eye Height: 6.468E-7

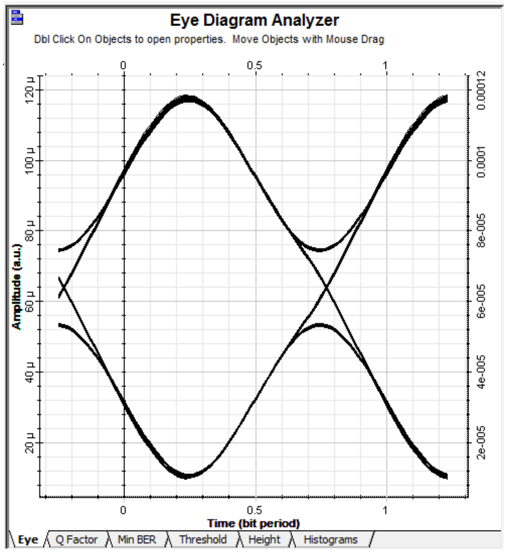
Simulation for Weak Turbulence (Cn = 1.00E-16) for different distance



Distance: 500m

Min BER = 0

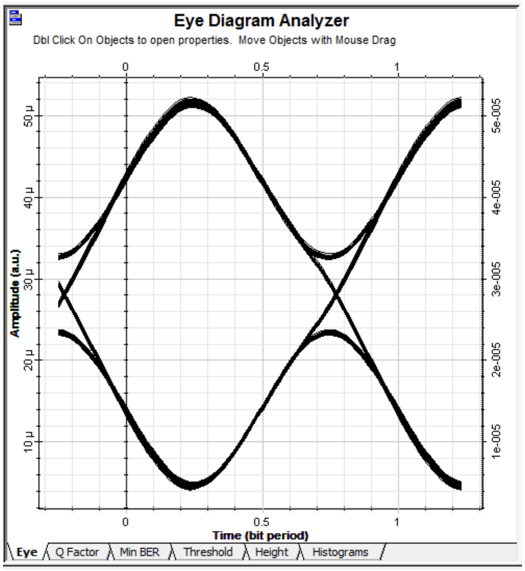
Max Eye Height: 0.00042



Distance: 1000m

Min BER = 0

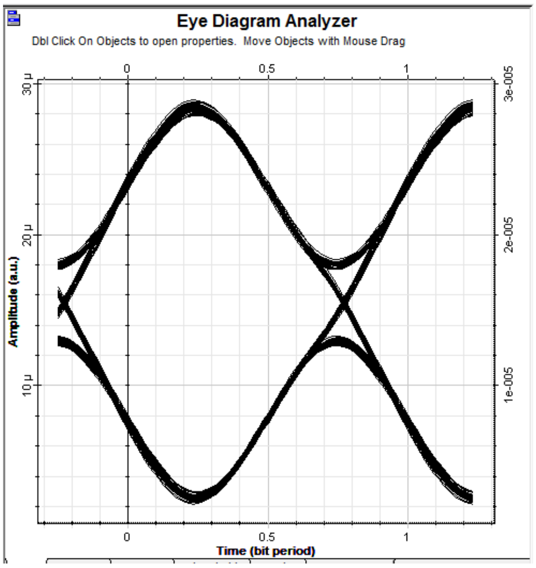
Max Eye Height: 0.000104



Distance: 1500m

Min BER = 0

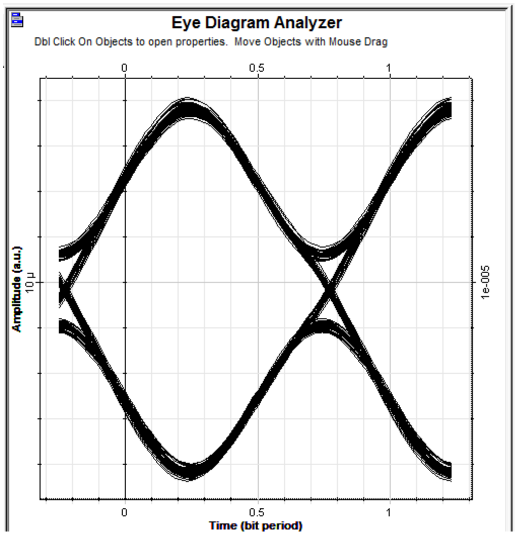
Max Eye Height: 4.554E-5



Distance: 2000m

Min BER = 0

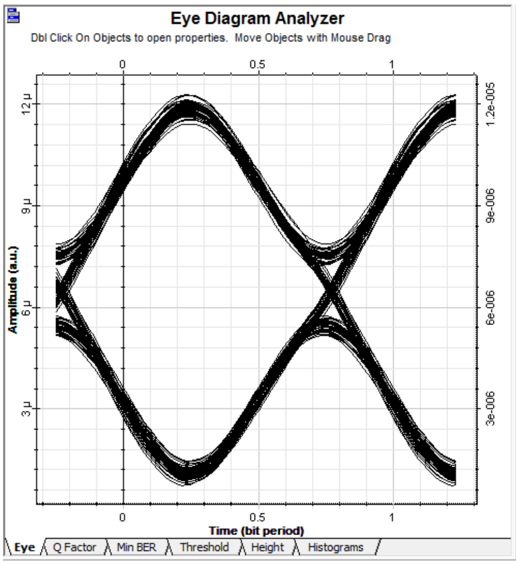
Max Eye Height: 2.468E-5



Distance: 2500m

Min BER = 0

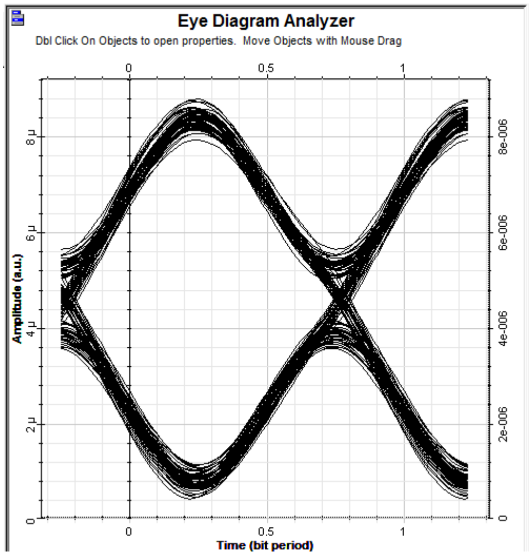
Max Eye Height: 1.510158E-5



Distance: 3000m

Min BER = 7.0715E-235

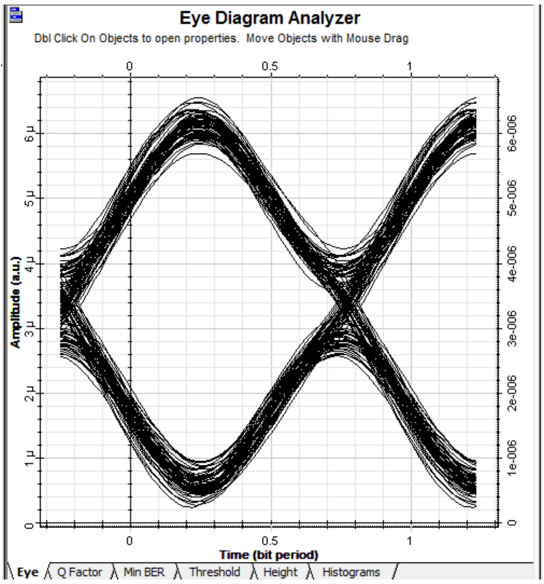
Max Eye Height: 9.7677E-6



Distance: 3500m

Min BER = 5.628E-122

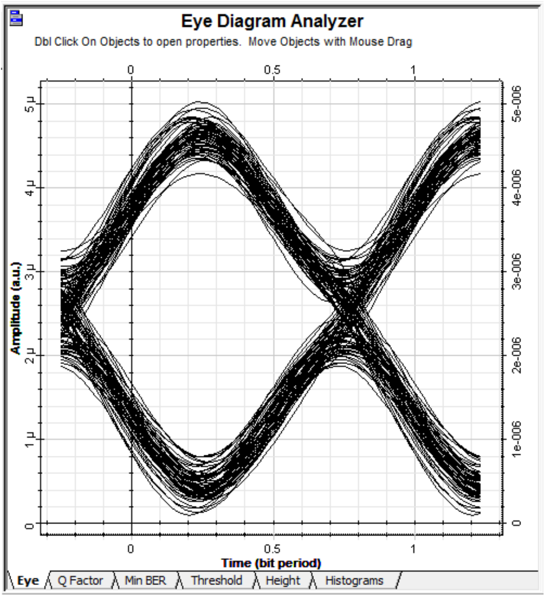
Max Eye Height: 6.6148E-6



Distance: 4000m

Min BER = 1.6377E-67

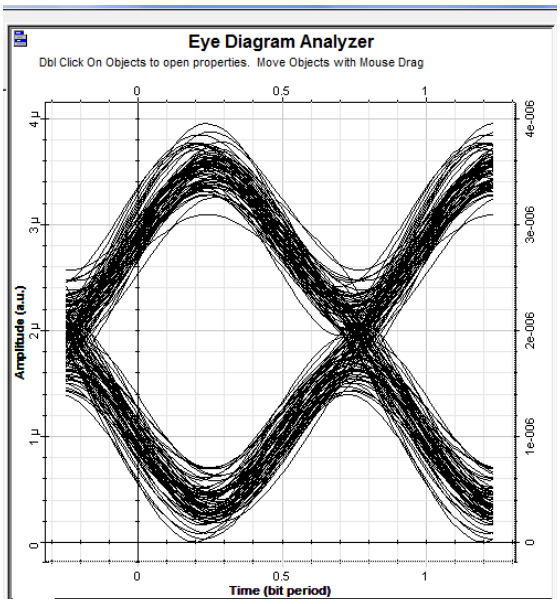
Max Eye Height: 4.5811E-6



Distance: 4500m

Min BER = 2.275E-39

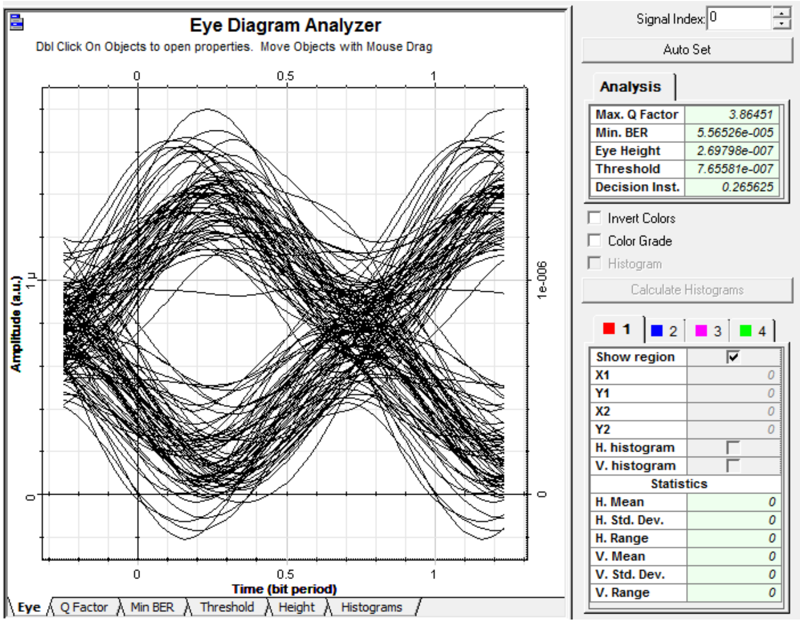
Max Eye Height: 3.19942E-6



Distance: 5000m

Min BER = 5.1719E-24

Max Eye Height: 2.223E-6



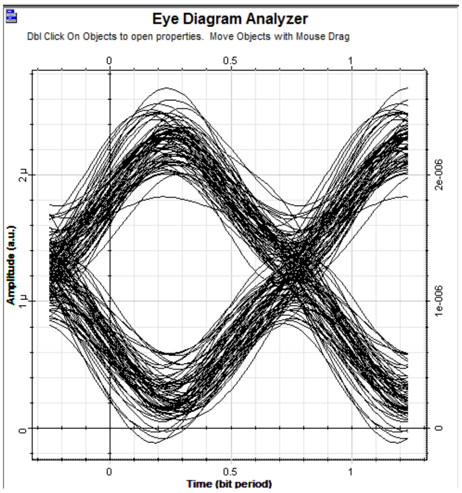
Distance 7000m

APPENDIX 3:

Simulation result in strong turbulence, distance 1500m but with parameters changed

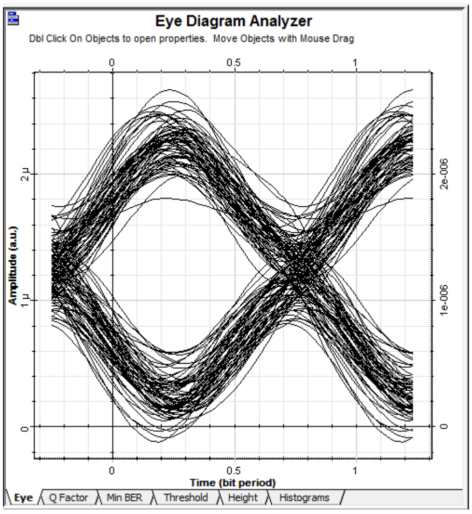
Simulation strong turbulence. Distance 1500m (the furthest it can go)

ORIGINAL SETTING



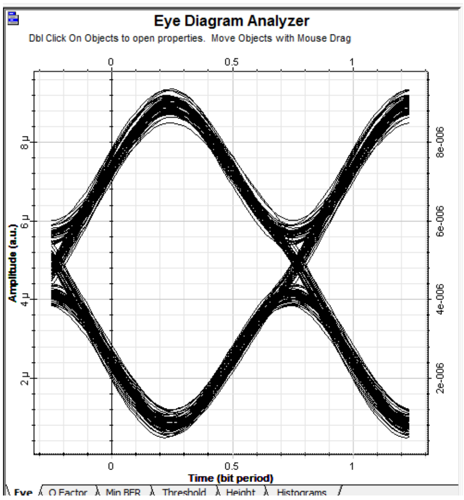
Min BER = 6.66423e-011
Max Eye Height: 1.07305e-006

Changing Transmitter Aperture Diameter from 5cm → 10cm



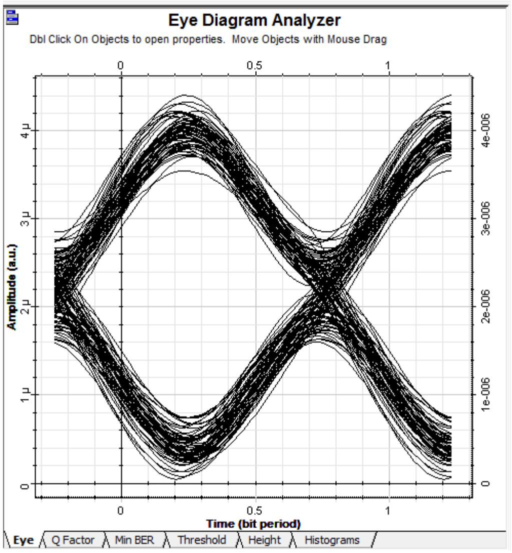
Min BER = 9.4038E-11
Max Eye Height: 1.056E-6

Changing Reciever Aperture Diameter from 20cm → 40cm



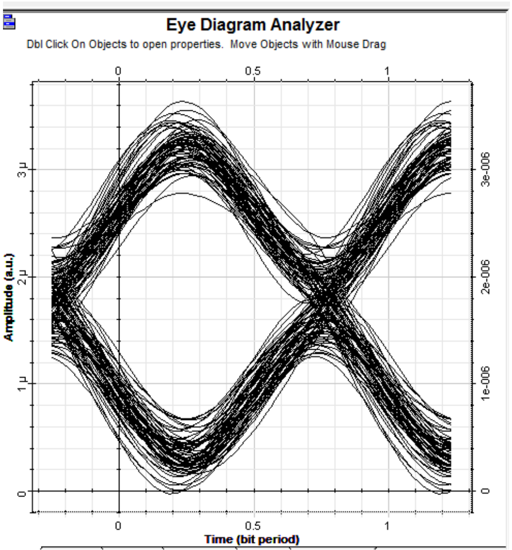
Min BER = 7.11242E-138
Max Eye Height: 7.12203E-6

Changing beam divergence from 8mrad → 6 mrad



Min BER = 5.58457E-30
Max Eye Height: 2.632E-6

Changing power from 70mW → 100mW



Min BER = 2.9997E-20
Max Eye Height: 1.937E-6